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Ultrasonic agitation of Kevlar fibres

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Kevlar 49 fibres exposed to ultrasonic waves suffer axial compression manifested by the introduction of kink bands, dispersion of fibrils and macrobuckling. Application of subsequent tensile load, however, influences the kink bands.

In polymer research, ultrasonic waves are traditionally used for the study of dynamic processes such as polymerization and degradation. Nondestructive testing of resins with ultrasonic waves is also well known. Reviews describing different types of studies on polymeric materials employing ultrasonic waves are available[1,2]. In this communication we present details of some observations concerning the residual effects of exposure to ultrasonic waves on the aramid fibre Kevlar.

A bundle of Kevlar 49 fibres (approximately 150 mm long and 2 mm thick) made commercially available by DuPont Inc. USA, was exposed to ultrasonic waves of frequency 40 ± 3 kHz generated by a fully transistorized ultrasonic generator. Distilled water was used as the transmitting medium. Figure 1 is a schematic representation of the experimental arrangement used. The generator and the tank containing the sample were coaxially connected. Fibres were subjected to cumulative exposure to ultrasonic waves for 1, 3 and 6 h respectively. The choice of the time intervals was purely arbitrary. In the course of the agitation, the distilled water surrounding the sample was getting heated, the temperature rising to ≈ 40°C after ≈ 2 h of agitation. At such stages, the agitation was disrupted and continued further only after the liquid returned to the ambient temperature of ≈ 25°C. Surface characteristics of ultrasonically agitated filaments were subsequently examined in an optical microscope using polarized light in the reflection geometry.

The most conspicuous effect of ultrasonic agitation on Kevlar fibres is the introduction of kink bands. Figure 2 compares the surface characteristics of Kevlar fibres both prior to and after ultrasonic agitation. Fibres agitated for 1 h include isolated, faint kink bands which are either normal or inclined to the fibre axis. In contrast, fibres agitated for 3 and 6 h exhibit a concentration of V- and X-shaped bands which are distinctly darker and more in number than the bands found in fibres agitated for 1 h. The V- and X-shaped bands are found almost continuously along the length of the agitated fibre. Kink bands, as is well known, correspond to structural deformation[3]. The bands which are inclined to the fibre length are attributed[4] to tangential deformation of the radially oriented molecular architecture[5] which characterizes Kevlar fibres and the perpendicular bands are correlated with radial splitting of the fibrils[4]. The V- and the X-shaped features represent multiple bands and they result from overlapping inclined and normal kink bands. The surface characteristics of Kevlar thus indicate that exposure to ultrasonic waves introduces structural deformations which in turn lead to the formation of kink bands and the severity of the deformation increases with increase in the duration of exposure.

Ultrasonic agitation is also found to cause dispersion of fibrils (Figure 3 *a*). The separated fibrils tend to get entangled around the main fibre with subsequent agitation (Figure 3 *b*). Figure 3 *c* shows another feature, viz. the macrobuckling. Along the length of the agitated fibre, notch-like regions of the type shown in Figure 3 *c* where fibre changes direction or buckles, have been observed. Conspicuously, the macrobuckling is less rampant than the formation of kink bands and also the dispersion of fibrils.

It must be pointed out that the formation of kink bands, separation of fibrils and macrobuckling are characteristics typical of axial compression of Kevlar fibres[6–8]. The remarkable similarity between the characteristics of the ultrasonically agitated and the axially compressed Kevlar fibres suggests that exposure to ultrasonic agitation causes axial compression. Occurrence of such axial compression is not surprising because the fibres were positionally unconstrained during the process of ultrasonic agitation. It is not unlikely that at some point of time they got favourably oriented to suffer axial compression by the continuously impinging ultrasonic waves.

The kink bands, both single as well as multiple, formed by ultrasonic agitation of Kevlar are found to be sensitive to subsequent tensile loading. The effect of tensile loading was followed by using a spring loaded

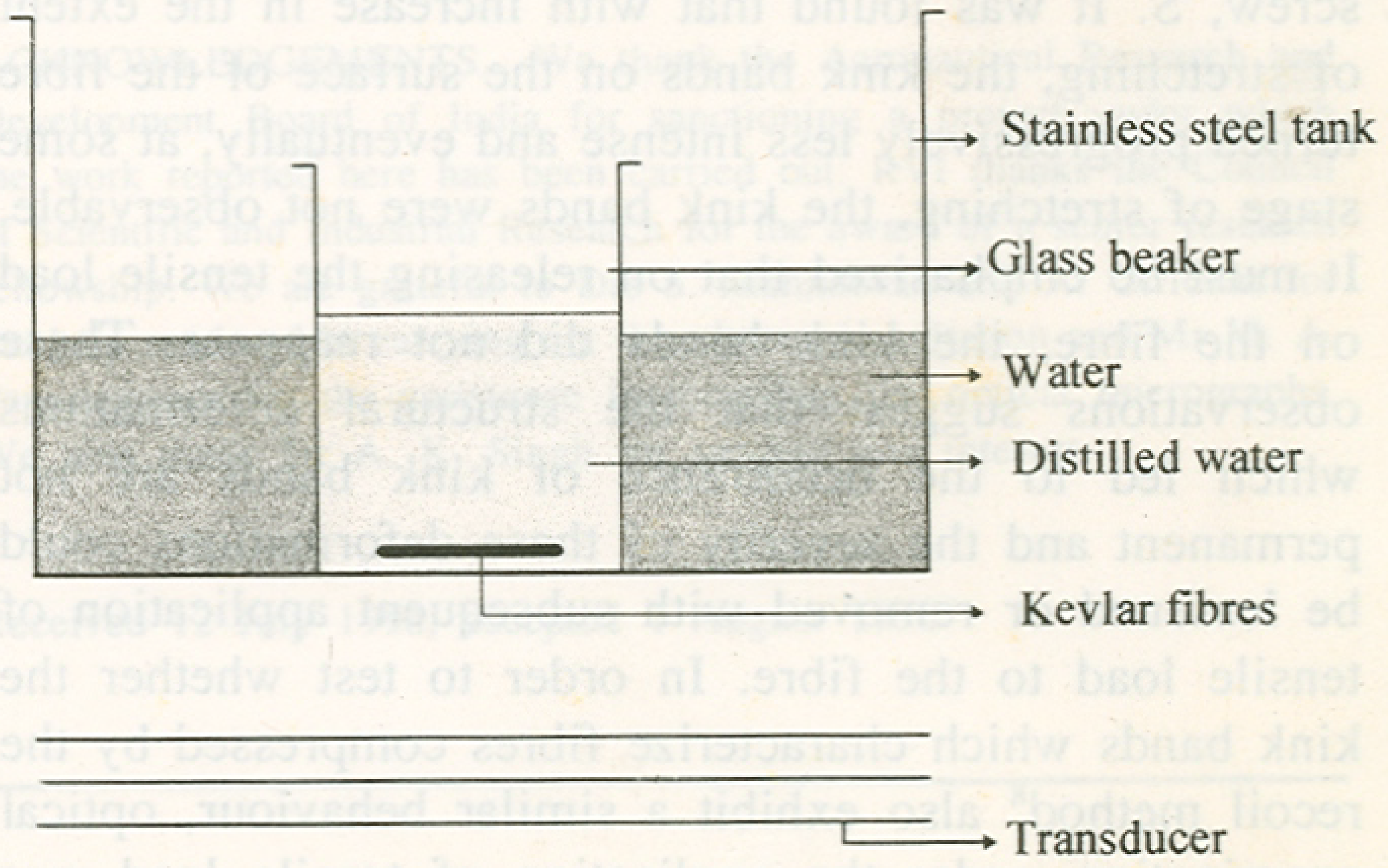

Figure 1. Schematic representation of the arrangement used for ultrasonic agitation.

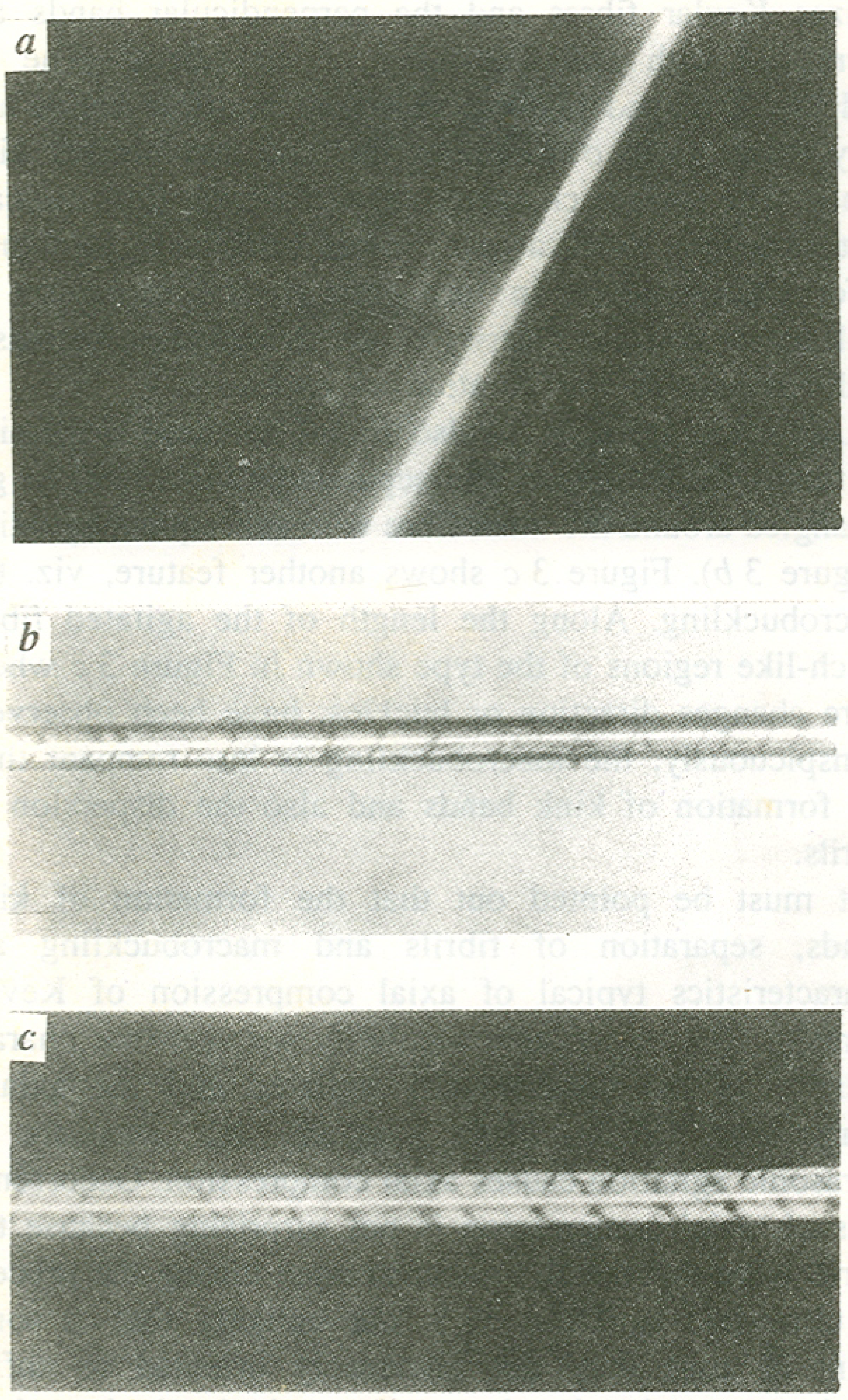

Figure 2 *a–c*. *a*, Surface of the ≈ 11 μm thin fibre prior to ultrasonic agitation; *b* and *c*, V- and X-shaped kink bands in fibres agitated for 3 and 6 h respectively.

device of the type shown in Figure 4. In this device the fibre held taut between the two sets of screws could be stretched to different extents by adjusting the lead screw, S. It was found that with increase in the extent of stretching, the kink bands on the surface of the fibre turned progressively less intense and eventually, at some stage of stretching, the kink bands were not observable. It must be emphasized that on releasing the tensile load on the fibre, the kink bands did not reappear. These observations suggest that the structural deformations which led to the occurrence of kink bands are not permanent and the severity of these deformations could be lessened or removed with subsequent application of tensile load to the fibre. In order to test whether the kink bands which characterize fibres compressed by the recoil method[8] also exhibit a similar behaviour, optical examination under the application of tensile load was extended to Kevlar fibres compressed by the recoil method. Interestingly, irrespective of the method of formation, under the application of tensile load, the kink

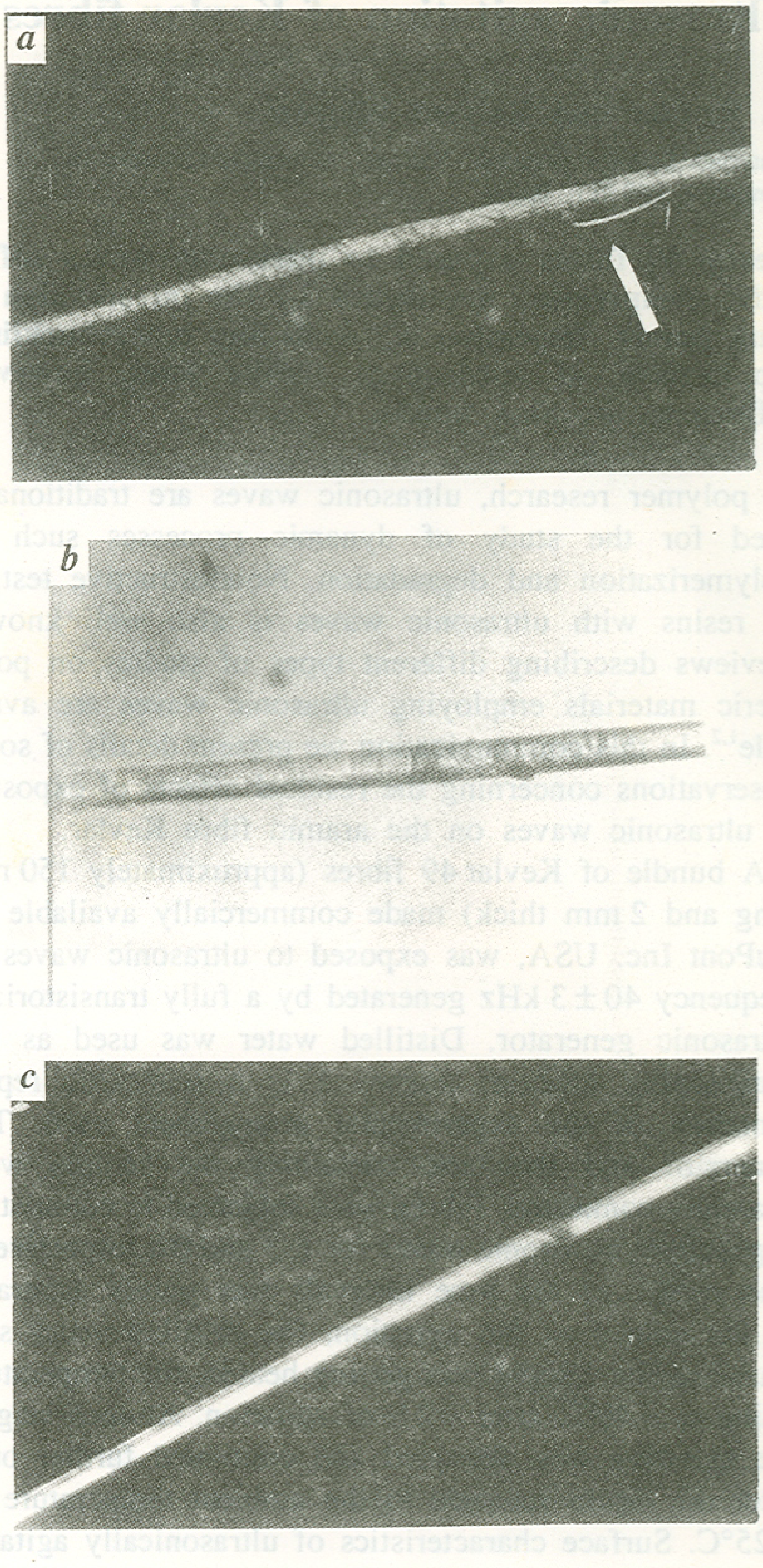

Figure 3 *a–c*. *a*, Dispersion of fibrils; *b*, Dispersed fibrils coil round the fibre; *c*, Macrobuckling of the fibre.

bands behaved in an identical fashion, viz. disappeared with the application of load. Figure 5 illustrates an example of the effect of stretching on kink bands. It must be pointed out that these observations pertain only to the surface of the fibre. Information on the effect of tensile load on ultrasonically induced deformations residing away from the surface and towards the core of the fibre is not available at the present moment. TEM observations are likely to provide insight into this aspect. It must be mentioned that in the present study, the stretching which the fibres were subjected to was not quantified. Consequently, calculations providing correlation between the tensile load and the energy needed for the removal of the deformation which caused the kink bands were not possible.

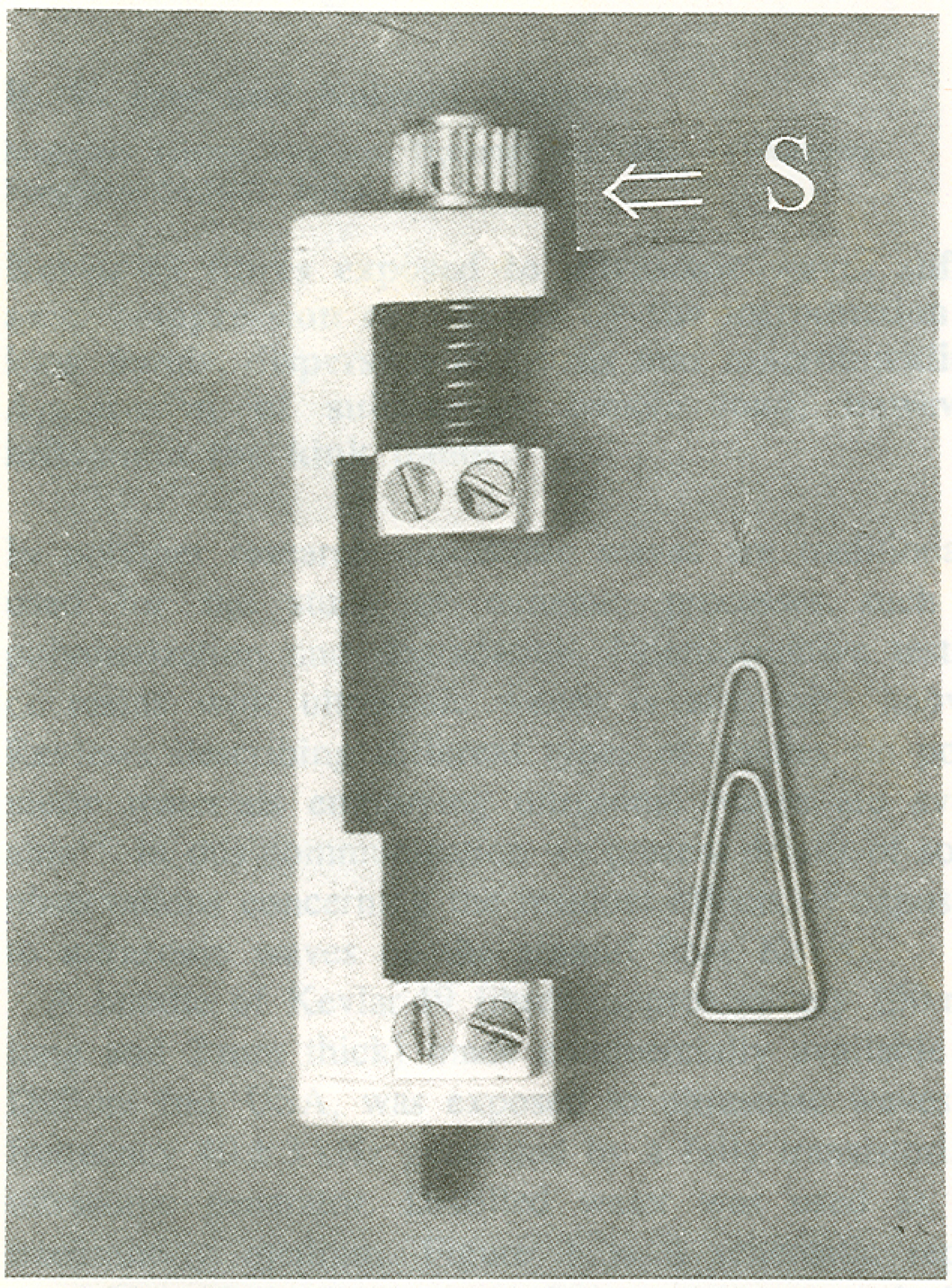

Figure 4. Device used for stretching the fibre.

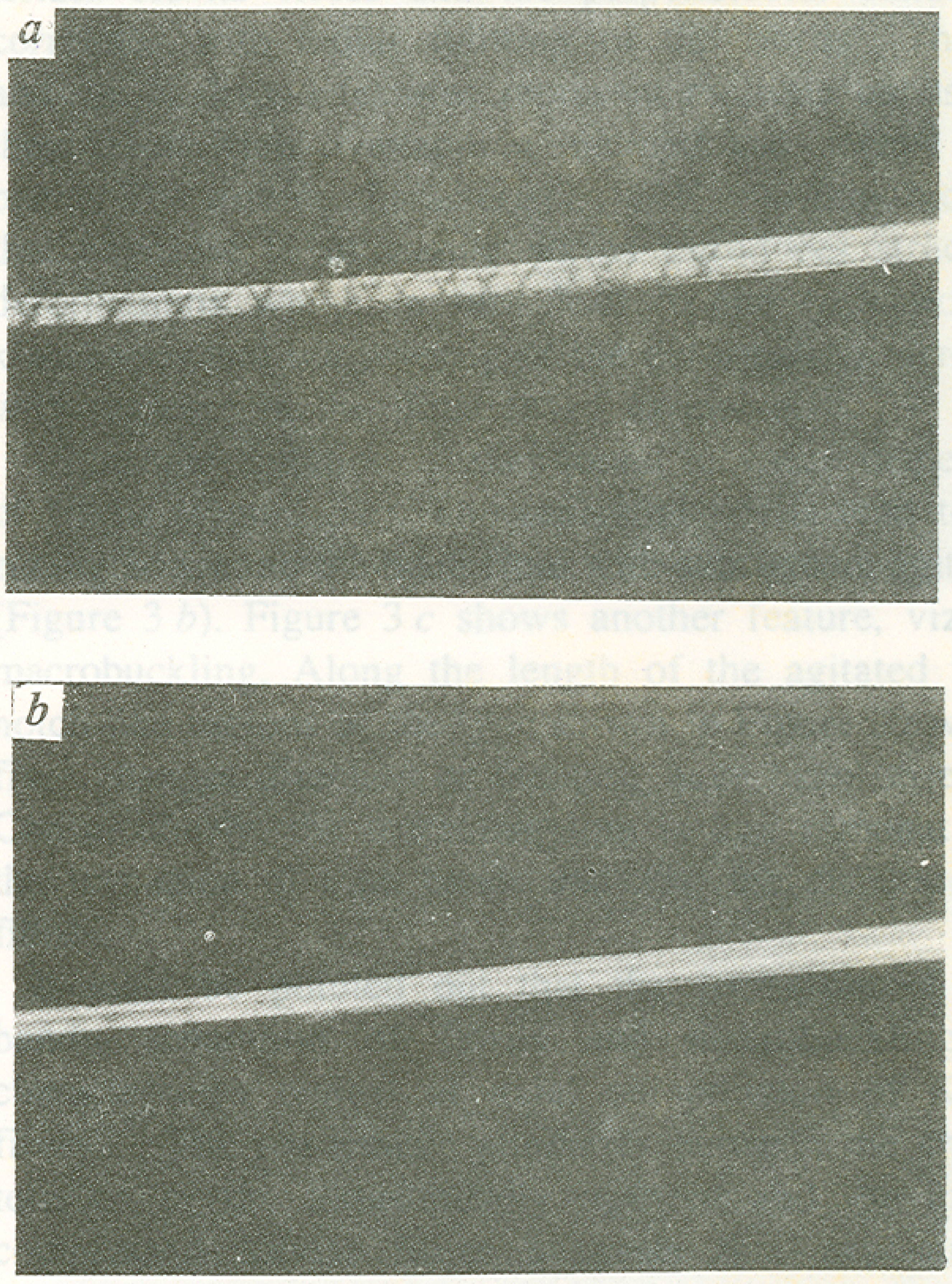

Figure 5. Kink bands: *a*, prior to and *b*, after stretching the ultrasonically agitated fibre.

In contrast with the kink bands, the macrobuckling introduced by ultrasonic agitation is not removed by subsequent stretching. The notch-like regions (Figure 3 *c*) representing change in direction thus appear to represent comparatively more severe and irreversible structural deformations introduced during ultrasonic agitation.

It must be mentioned that Allen and Roche[9] have observed a similar effect of tensile load on Kevlar fibres. Their observations indicate that the pleated structure[10] which characterizes Kevlar gets straightened with the application of tensile load. However, in contrast with the kink bands, the pleats reappear with the removal of the load.

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